Shoaling Wave Energy Dissipation in Turbulent Bottom Boundary Layers

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LONG-TERM GOALS

The long-term goal is to increase the understanding and predictive capability for effects of turbulent bottom boundary layers on shoaling wave fields.

OBJECTIVES

Shoaling surface waves can create turbulent boundary layers at the sea floor that make significant contributions to wave energetics, dissipation rates, and fluid-sediment interactions. The objective is to make direct estimates of wave energy dissipation rates in the bottom boundary layer and to develop predictive capabilities for these effects as a function of important environmental parameters, such as wave heights, frequency spectra, local water depth, bottom roughness (including sand ripples), and mean current conditions. Three-dimensional numerical simulations are also being used to evaluate the performance of one-dimensional eddy viscosity models for the bottom boundary layer.

APPROACH

The work involves theoretical analysis, numerical computations, and comparison with field and laboratory results. The primary experimental tools are three-dimensional direct numerical simulations (DNS) (*e.g.*, Slinn and Riley, 1998) and large eddy simulations (LES) (*e.g.*, Winters *et al*., 2000) of the wave bottom boundary layer that resolve the relevant scales of motion in the shear layer at the sea-bed.

WORK COMPLETED

We have completed a study focusing on oscillatory flows over a smooth bottom surfaces including mean currents of varying strength in the direction normal to the wave oscillations. We have also completed a study for a small set of conditions of oscillatory flow over small scale topographic variability (*e.g.*, sand ripples) in collaboration with Kraig Winters (University of Washington).

RESULTS

A computational model has been adapted (from Winters *et al*., 2000) to solve the three-dimensional Navier–Stokes equations for an incompressible, constant density, flow in a terrain–following coordinate system (σ–coordinates). We examine a small, horizontally periodic domain representative of oscillatory flow over periodic topography using DNS and LES. The WBBL over a "sand" ripple is

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significantly more turbulent throughout the full flow period than over a flat bottom (see Figure 3 below).

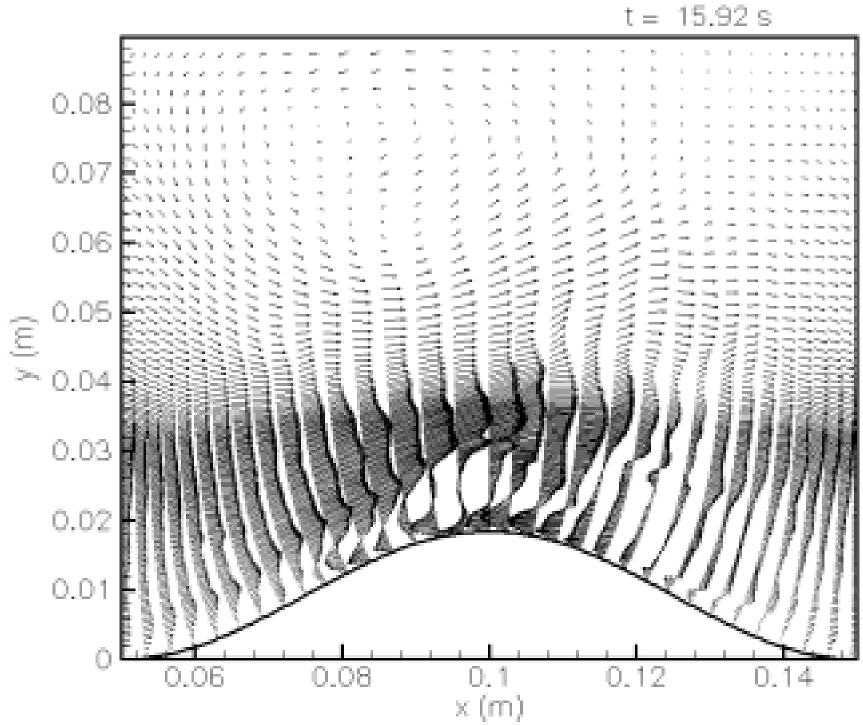

Figure 1: Velocity vectors in a 2-D plane (from a 3-D simulation) of oscillatory flow over a sinusoidal sand ripple during a phase near flow reversal, only 1/8 of the velocity vectors in this plane are shown.

Flow over variable topography is illustrated in Figures 1 and 2. Figure 1 depicts velocity vectors during a phase of flow reversal over a sinusoidal sand ripple with amplitude of 1.8 cm and wavelength of 10 cm. The boundary layer thickness increases and the duration of turbulent bursts is longer than flow over a smooth surface. Flow separation occurs in the lee of the ripple crests during phases of strong onshore or offshore flow, and strong flow instabilities develop during flow reversal near the bedform.

Figure 2 illustrates the *y*-component of the vorticity field in the center plane over a sand ripple during a phase of maximum flow. For these experiments, the bottom topography is chosen to match natural conditions that develop in the laboratory (Ransoma and Sleath, 1994), that is, the ripple dimensions are set by the near bed wave-orbital excursion length. For the conditions chosen, with a maximum wave induced current of 20 cm/s and a period of 2.45 s, the bottom boundary layer over a smooth bed remains laminar. As the ripple geometry is made progressivley steeper (not shown), like a cnoidal wave, the turbulence intensifies and becomes more localized over the crest of the bed forms. Turbulent bursts still occur most strongly at phases of flow reversal. The bursts originating during flow reversal, however, are not damped out during flow acceleration, but remain strong throughout the wave period. Thus, the shoaling wave energy dissipation rates are enhanced in boundary layers over ripples compared to flows over smooth topography. A complex flow develops even for the simplest

wave field forcing conditions. The shear stress on the boundary is highly variable temporally and spatially with the strongest shears occurring on the front and crests of the ripple.

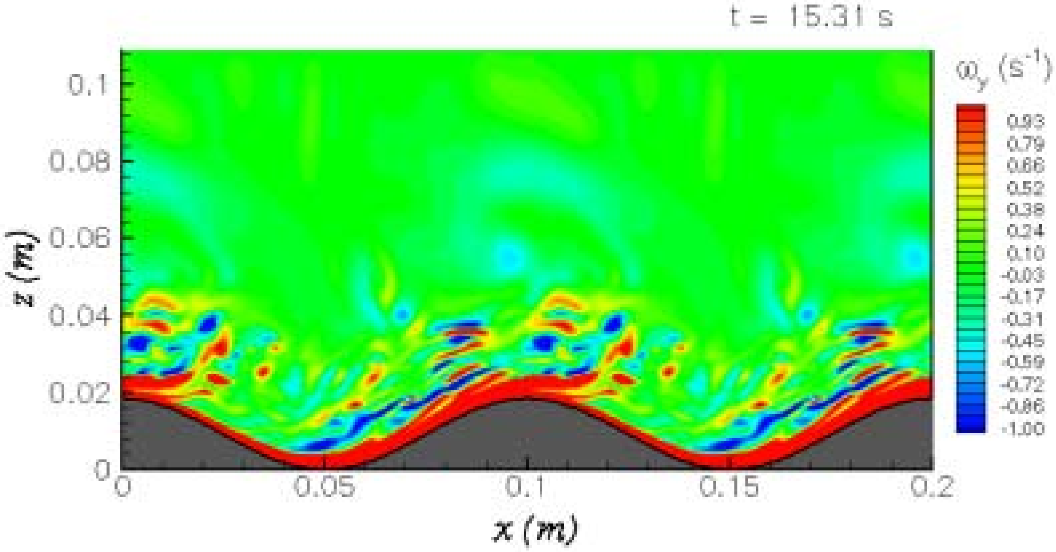

Figure2: Vorticity fields in a 2-D plane (from a 3-D simulation) of oscillatory flow over a sinusoidal crested sand ripple at a phases of maximum flow.

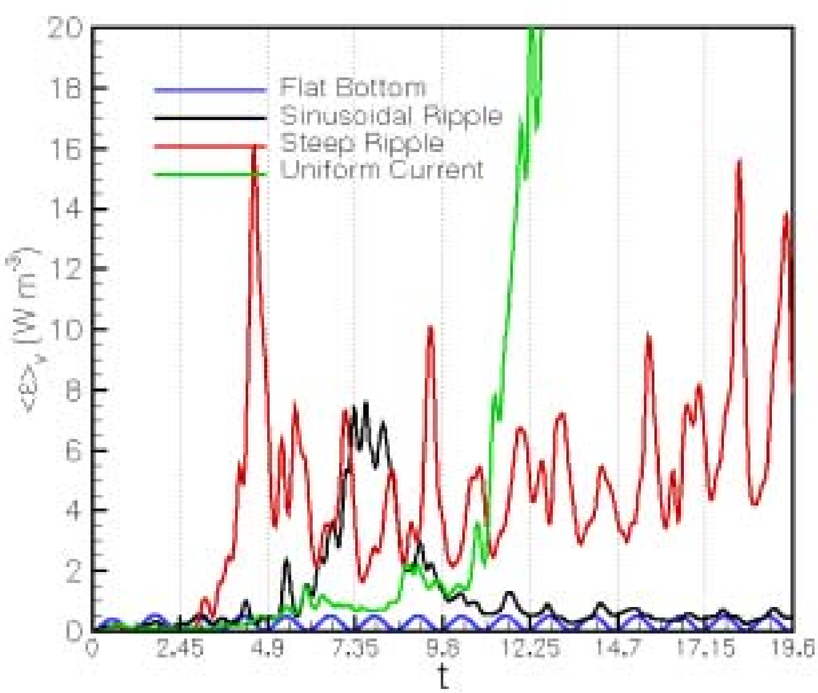

Figure 3: Volume averaged kinetic energy dissipation rate for three different WBBL experiments with different bedforms, and one steady flow experiment over a steep crested ripple.

Figure 3 shows the volume averaged kinetic energy dissipation rates for four related experiments. The blue curve shows the dissipation rate in the wave bottom boundary layer over a flat bottom, the black curve is the dissipation rate over the sinusoidal ripple, the red curve is the dissipation rate for the same wave forcing conditions but with a steeper shape of sand ripple (but same ripple amplitude and wavelength) and the green curve is for the same steep ripple, but forced with a steady uni-directional current with the free stream velocity of 20 cm/s, the maximum wave induced velocity for the oscillatory flow experiments. The results show a strong sensitivity to the shape of the bedform, also there are strong variations in the flow field as a function of time. Initially the flow over the sine wave becomes strongly turbulent after about 3 wave periods (t = 7.35 s), but it establishes a new equilibrium with lower levels of dissipation after the initial turbulent events decay. The flow over the steep ripple, continues to generate turbulence and higher dissipation rates throughout the simulation, comparable to the levels initially obtained in the flow over the sine wave. The boundary layer thickness and dissipation rates increase steadily for the uni-directional flow as expected as the Reynolds number based on the downstream distance continues to grow in time.

IMPACT/APPLICATIONS

Small-scale boundary layer processes at the sea bed in shallow water are strongly influenced by wave motions and are key to understanding issues such as beach erosion and protection, bottom morphology, water clarity, mine burial, surface wave energy budgets, and bottom friction experienced by mean currents. Our work is an effective means of developing and testing parameterizations for small-scale processes that must be considered in larger scale modeling efforts.

TRANSITIONS

Our work has taken a new direction through discussions with Tim Stanton (Naval Postgraduate School) based on results from measurements of the WBBL during SHOWEX. We are now emphasizing flow behavior over rough topography characteristic of that environment. The field data is input to our numerical experiments and output aids in interpreting the field observations to develop optimal models for estimating dissipation rates. Our intention is to focus on sheet flow conditions in the next phase of the work.

RELATED PROJECTS

1-Tim Stanton and Ed Thornton at the Naval Postgraduate School are making field measurements as a part of the ONR DRI on Shoaling Surface Waves.

2- Kraig Winters at the University of Washington has been instrumental in developing the model for flow over complex topography.

3-D.N. Slinn, Office of Naval Research, 321CD, Coastal Dynamics, Nonlinear Time Dependent Currents in the Surfzone. 1999-2002. Coupling of wave field and mean current interactions is the focus of this intermediate scale nearshore modeling study. Simple parameterizations for bottom boundary layer dissipation that are employed can be improved by insight gained from the WBBL study.

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